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The Use of Enlarged Feed Wells as Flocculator Units in Activated Sludge Secondary Clarifiers

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THE USE OF ENLARGED FEED WELLS AS FLOCCULATOR UNITS IN ACTIVATED SLUDGE SECONDARY CLARIFIERS

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ABSTRACT

The quality of the effluent from activated sludge wastewater treatment plants is highly dependent on the performance of the final clarifier. The final clarifier performs solids/liquid separation through sedimentation. The standard design criteria (overflow rate and detention time) must be selected such that the effluent suspended solids requirements are met.

Numerous research programs have been conducted to evaluate the factors affecting the sedimentation efficiency of activated sludge mixed liquor. Flocculation has been documented as a significant factor. The flocculation process is an agglomeration of small primary particles on the surface of larger particles to achieve higher settling velocities. Increased settling velocities promote enhanced sedimentation efficiencies.

This research reports on some design aspects of clarifier feed wells and the associated impact on the flocculation process. A number of experiments were conducted using a clarifier with a fixed diameter. The effluent suspended solids concentration was evaluated for different feed well diameters. In the seven experiments performed, the feed well diameter was varied from 2 to 5.5 inches with a constant clarifier diameter of 8 inches. An enlarged feed well diameter provides longer detention times in the feed well and, hence, promotes solid contact and flocculation.

The experimental results, however, indicate that use of a larger feed well diameter increases the effluent suspended solids. In the clarifier used for the experiments, the clarification zone was concentric with the feed well. Any increase in the feed well diameter produced a decrease in the available clarification zone. The reduced clarification zone resulted in a shorter detention time for clarification and an increase in overflow rate. The decreased available detention time together with the associated increase in overflow rate negated any beneficial effect of enhanced flocculation in the larger feed well.

In the range of values in the experimental program, a feed well diameter of 25% of the clarifier diameter was found to yield the best results with respect to effluent suspended solids. This value appears to be a fair trade-off between improved flocculation in an enlarged feed well and impaired suspended solids removal due to a shorter detention time and an increased overflow rate in the clarification zone. This optimum configuration appears to be consistent with current practice.

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CHAPTER I

INTRODUCTION

Activated sludge is a process for conversion of organic wastes to a more stable form. As a result of the stabilization, a large quantity of cellular mass is produced which can be separated from the waste stream in a secondary clarifier. Biological solids entering the secondary clarifier are predominantly bacterial in nature and flocculent in form (Baker and Reed 1984).

Because of the nature of the solids, a strong relationship between BOD (biological oxygen demand) and effluent suspended solids (SS) is expected (Loehr and de Navarra 1969, Dick 1970, Pipes 1979 and Novak 1983). Association of effluent suspended solids with BOD may cause significant problems to maintain compliance with effluent BOD standards. The correlation between suspended solids and BOD in the effluent from municipal activated sludge facilities has been reported by several researchers, as summarized in Table 1.

TABLE 1

RELATIONSHIP BETWEEN EFFLUENT SUSPENDED SOLIDS AND BOD CONCENTRATIONS

SOURCE	TOTAL BOD IN EFFLUENT (mg/l)
Loehr and de Navarra (1969)	BOD = 15 + 0.43 SS
Dick (1970)	BOD = 10 + 0.6 SS
Pipes (1979)	BOD = 8.8 + 0.61 SS

Table 1 indicates that 1 mg/l of effluent suspended solids exerts an average value of 0.55 mg/l of BOD. Even if all the influent BOD is removed in the aeration tank as sludge, the overall performance of the activated sludge system depends strongly on solid-liquid separation in the secondary clarifier. This phenomenon is controlled mainly by physical properties of particles in the sludge as well as by the configuration of the secondary clarifier.

Solids entering the secondary clarifier have a tendency to flocculate. Class 2 particles are defined as particles which have a tendency to flocculate during sedimentation, with an associated increase in size and settling velocity. It has been well documented that sedimentation of class 2 particles is influenced significantly by detention time.

An enlarged feed well diameter would provide additional detention time for solids contact. Agglomeration of small particles would be expected, which results in larger floc diameters and enhanced particle settling velocities. One would expect that higher settling velocities would improve the solids removal efficiency.

The objective of this research is to determine the effect on suspended solids removal efficiency associated with variation in the feed well diameter for clarification of activated sludge mixed liquor. Feed well detentions in excess of values normally used in practice were considered in the experimental program.

CHAPTER II

LITERATURE REVIEW

In the literature for activated sludge processes, some characteristics of the aeration basin such as organic loading, dissolved oxygen concentration (D.O.) and mean cell residence time have been documented to influence the physical properties of the mixed liquor flocs (Sezgin et al. 1978). The properties of these flocs may limit the ability of the basin to produce a well-clarified effluent.

The occurrence of sludge bulking, or pin-floc, is the result of improper biological characteristics or physical conditions in the aeration basin. Sludge bulking is normally a consequence of excessive growth of filamentous microorganisms, which build a rigid backbone for the flocs, to which flocculent zoogleal microorganisms attach. In the case of sludge bulking, the filaments protrude out of the general confines of the flocs into the bulk medium. This bridging interferes with the close contact of the floc particles, and results in slow settling (Sezgin et al. 1978). On the other hand, insufficient filaments may cause the floc to be weak. Insufficient floc strength may be a factor in floc break-up in the turbulent environment of the aeration basin, with development of finely dispersed particles in the secondary clarifier. Assuming the mixed liquor entering the secondary clarifier has been properly processed in the aeration basin, the quality of the effluent depends on the characteristics of the secondary clarifier.

For the secondary clarifier, overflow rate and detention time have been recognized as the principal design criteria. Recommended overflow rates for secondary clarifiers have been lowered from earlier practices, to improve suspended solids removal efficiency. The 1959 joint publication of the American Society of Civil Engineers and the Water Pollution Control Federation design manual suggested overflow rates of approximately 1000 gal/day-ft^2 for design flows greater than 2.0 MGD (Joint Committee of the American Society of Civil Engineers and the Water Pollution Control Federation 1959). A subsequent edition of this design manual was published in 1977, in which an overflow rate of 800 gal/day-ft^2 was recommended (Joint Committee of the American Society of Civil Engineers and the Water Pollution Control Federation 1977). As discussed later in this chapter, overflow rate and detention time are interrelated. For a basin of fixed geometry, a longer detention time would result from a lower overflow rate. A longer detention time promotes solids contact and, hence, the flocculation process for developing larger particles. Larger particles will have higher settling velocities.

The influence of these factors (overflow rate, detention time and flocculation/solids contact) are discussed in more detail in the remaining part of this chapter.

Flocculation/Solids Contact

Flocculation is the aggregation of colloidal particles that result in larger flocs. This process enhances the settling velocities of the particles, as is justified by the following equation (Reynolds 1977) which can be developed from a force balance for spherical particles:

$$Vs = [\nu \frac{4g}{3\ CD} (Ss - 1)\ d]^{\frac{1}{2}} \tag{1}$$

For laminar flow at low Reynolds numbers ($R < 0.5$):

$$CD = \frac{24}{R} \tag{2}$$

$$CD = \frac{24\nu}{Vs\ d} \tag{3}$$

Substituting equation (1) into equation (3) results in Stoke's Law:

$$Vs = \frac{g}{18\nu} (Ss - 1)\ d^2 \tag{4}$$

where:

Vs = settling velocity, cm/sec

CD = drag coefficient

g = acceleration due to gravity, cm/sec^2

Ss = specific gravity of the particles

d = particle diameter, cm

ν = kinematic viscosity of water, cm^2/sec

R = Reynold's Number

Stoke's Law indicates that particles with larger diameters will have higher settling velocities.

Figure 1 presents a typical mixed liquor particle size distribution (Parker 1983). A bimodal size distribution is found with flocs (25 to 1600 μm) and primary particles of bacterial size (0.5 to 5 μm). There was no indication of particles in the size range of 5 to 25 μm and 0.1 to 0.5 μm. The sedimentation efficiency of this mixed liquor during batch sedimentation testing is shown in Figure 2. The sedimentation occurs as a hindered settling process. This phenomenon creates a clear interface between the settling solids and the supernatant in the batch test (Parker 1983).

It is apparent from Figure 2 that settling favors larger particles, as predicted by Stoke's Law. The majority of primary particles less than 5 μm appear in the supernatant due to low settling velocities.

In the activated sludge process, the physical properties of a floc, such as size and density, are determined by conditions in the aeration basin. Floc break-up is favored in an aeration basin due to the highly turbulent environment of the basin. Turbulence is characterized by the velocity gradient (G), defined as follows (Reynolds 1977):

$$G = (P/\mu V)^{\frac{1}{2}} \tag{5}$$

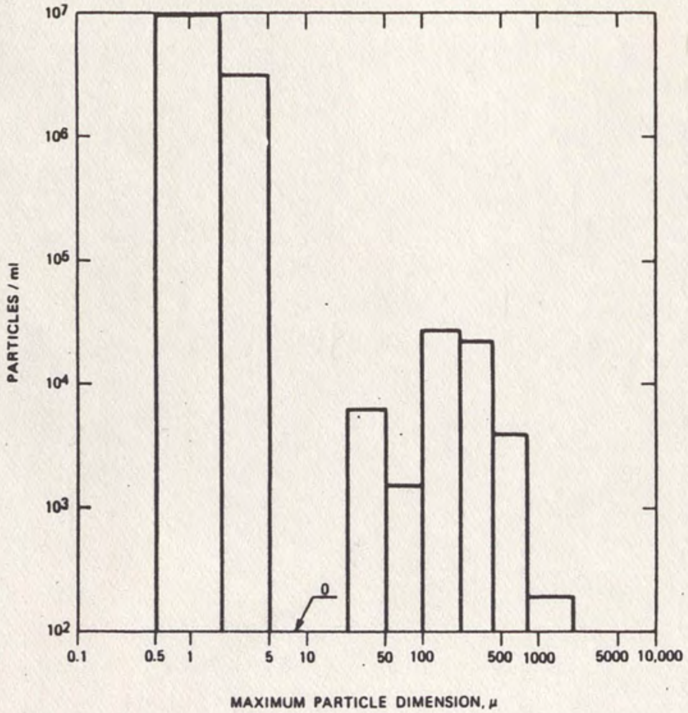

Figure 1. Typical Mixed Liquor Particle Size Distribution (Parker 1983).

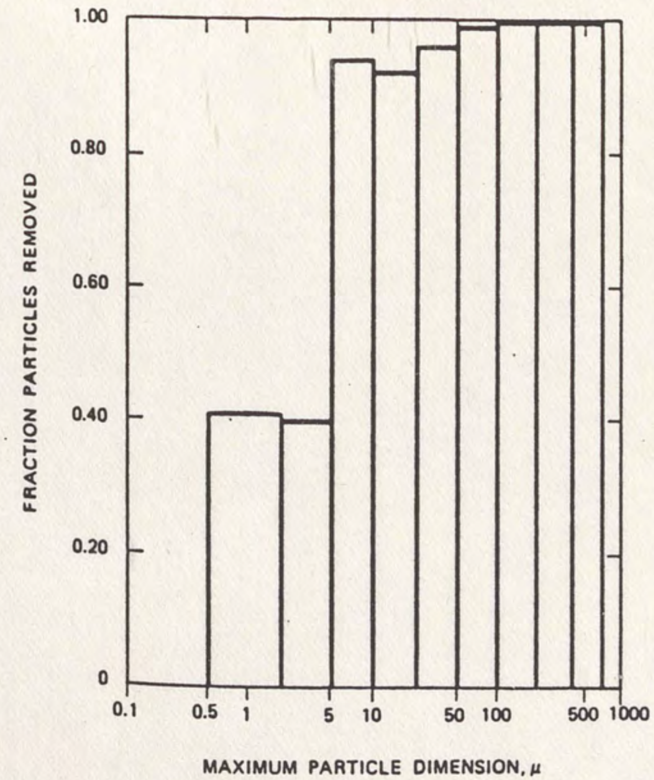

Figure 2. Sedimentation Efficiency Versus Particle Size Under Quiescent Conditions (Parker 1983).

where:

G = velocity gradient, sec^{-1}

P = power imparted to the water, ft-lb_f/sec

V = basin volume, ft^3

μ = absolute viscosity, lb_f-sec/ft^2

From a survey of 19 activated sludge plants, Parker (1983) reported a range of G values from 88 to 220 sec^{-1}. The field data from 5 of these plants indicated an optimum G value with respect to the dispersion of the primary particles in the range of 20 to 70 sec^{-1}. In order to maintain the solids in suspension, and to achieve economical oxygen transfer, G values are typically in excess of 88 sec^{-1}.

Parker (1971) showed empirically that high G values tend to correlate with floc break-up. In his model he considered the break-up to result from surface erosion. The erosion is caused by shearing forces generated by fluid motion relative to the floc. The break-up occurs when the shear strength of the bonds joining the primary particles to a floc is exceeded. Additional flocculation of the particles after aeration but prior to or during sedimentation may enhance performance of the secondary clarifier, if particle growth is achieved.

Overflow Rate/Detention Time

Overflow rate has been generally accepted as a design criterion and is given as follows (Reynolds 1977):

$$Vo = \frac{Q}{Ap} \tag{6}$$

where:

Vo = overflow rate, gal/day-ft^2

Q = effluent flow, gal/day

Ap = cross-sectional area of the basin, ft^2

The following demonstration is provided to verify that the overflow rate can be expressed as a velocity term. The detention time in the clarifier is equal to the volume divided by the flow:

$$t = \left(\frac{Ap\ h}{Q}\right) \times 179.5 \tag{7}$$

or:

$$\frac{t}{h} = \frac{Ap}{Q}\,(179.5) \tag{8}$$

where:

h = the depth of the clarifier, ft

t = the detention time in the clarifier, hour

179.5 = conversion factor (gal-hr/day-ft^3)

The reciprocal of equation (8) yields the following relationship:

$$\frac{h}{t} = \frac{Q}{Ap}\left(\frac{1}{179.5}\right) \tag{9}$$

Multiplying both sides of equation (6) by $\left(\frac{1}{179.5}\right)$ and then substituting it in equation (9) yields the following expression:

$$Vo = \frac{h}{t} \tag{10}$$

Thus, the overflow rate can be expressed as a velocity equal to the clarifier depth divided by the hydraulic residence time.

Camp's analysis of the fractional removal efficiency of particles indicated that the particles with a settling velocity equal to or greater than the overflow rate will be completely removed (Camp 1946). The total amount of particles removed from the supernatant at any time t at the level in question would be equal to:

$$R = Ap\ C\ \min(Vo,Vs)\ t\ (28.3) \tag{11}$$

where:

C	=	concentration of the particles above the level in question, mg/l
Vs	=	settling velocity of particles, ft/hr
t	=	time of settling, hr
R	=	total amount of particles removed from supernatant, mg (Fitch 1958)
min(Vo,Vs)	=	select the minimum value
28.3	=	conversion factor, liters/ft^3

The minimum value of (Vo,Vs) must be selected since the fraction of particles removed (equation 13) cannot be more than 100 percent. The quantity Roo of the particles originally present in the height h is:

$$Roo = Ap\ C\ h\ (28.3) \tag{12}$$

Therefore, the fraction of particles removed (r) is:

$$r = \frac{R}{Roo} = \frac{Ap\ C\ \min(Vs, Vo)\ t}{Ap\ C\ h} \tag{13}$$

$$= \frac{\min(Vs, Vo)\ t}{h}$$

Substituting into equation (10), the following relationship results:

$$r = \frac{\min(Vs, Vo)}{Vo} \tag{14}$$

As summarized in Table 2, Parker (1983) calculated removal efficiencies for the various particle sizes noted in Figure 1 for a secondary sedimentation tank with an assumed overflow rate of 0.0236 cm/sec (500 gal/day-ft^2) and a floc density of 1.1 g/cm^3. The settling velocities in the table were calculated with equation (4) and the fractional removals were calculated with equation (14).

TABLE 2

FRACTIONAL REMOVAL EFFICIENCY OF DIFFERENT SIZE FLOC

FLOC SIZE (μm)	STOKE'S SETTLING VELOCITY (cm/sec)	FRACTIONAL REMOVAL AT OVERFLOW RATE (0.02369 cm/sec)
75	0.0306	1.0
50	0.0136	0.75
25	0.0034	0.14
10	0.00054	0.023
5	0.00014	0.005

SOURCE: Parker (1983)

As noted in Table 2, the larger particles which have settling velocities greater to or equal to the overflow rate will be completely removed, whereas particles with very small sizes have no chance of removal in the gravity sedimentation process, unless they are trapped by larger flocs during flocculation. Any factor that can enhance the flocculation process may, therefore, strongly influence the removal efficiency of the particles. One of these factors is known to be the detention time. A greater detention time provides an opportunity for more particle collisions, thus enhancing flocculation. The detention time is given as follows (Fitch 1958).

$$t = \frac{h}{Vo} \times 179.5 \tag{15}$$

where:

t	=	detention time, hr
h	=	clarifier depth, ft
Vo	=	overflow rate, gal/day-ft^2
179.5	=	conversion factor, (gal-hr/day-ft^3)

The dependence of the detention time on the overflow rate is clearly shown in equation (15) for a clarifier of fixed depth. The equation indicates that a higher detention time can be achieved by lowering the overflow rate, achieving a higher solids removal efficiency. In this case, for a fixed dimension clarifier, it is impossible to distinguish between the influence of these two factors on removal efficiency. But if flexibility exists, the higher detention time can be achieved by deeper tanks. In this case, at a constant overflow rate, the effect of the detention time can be evaluated independently of overflow rate by variation of depth. Previous laboratory studies have been conducted in this manner to examine the relative importance of these two design variables.

Dietz/Keinath Study

Dietz and Keinath (1984) reported the individual effect of overflow rate and detention time in the clear zone of the clarifier on the suspended solids removal. In their report, the relevant detention time was considered to be the detention time in the clear zone above the feed well since the feed dispersed into a dilute blanket.

A total of 16 continuous steady-state experiments were completed at two independent variables, overflow rate and detention time. Control of the detention time in the clear zone of the clarifier was achieved by variation of the feed well submergence.

The results from the 16 steady-state experiments indicated that the effluent suspended solids is affected more by detention time rather than overflow rate. A statistical study of these results was also made to evaluate the individual significance of the variables mentioned above. Based on an analysis of variance, Dietz and Keinath (1984) reported that the removal of suspended solids was enhanced by an increase in clear zone detention time. The effect of overflow rate on the removal of suspended solids was not shown to be statistically significant.

The stated conclusions would appear to conflict with accepted design practice in which overflow rate receives dominant priority in the design of the clarifier. Considering the inverse relationship between overflow rate and detention time (equation 15), a decrease in overflow rate causes an increase in the corresponding detention time. Therefore, the great consideration given to overflow rate as a design parameter may be explained in terms of the associated effect on detention time (Dietz and Keinath 1984).

Fitch Study

Fitch (1958) showed the relationship between percent removal of flocculent particles, overflow rate and detention time for an "ideal" sedimentation tank, as presented in Figure 3.

The data presented in Figure 3 were generated from class 2 particles in batch settling tests. The relationship between batch and continuous sedimentation tanks was developed with the aid of Camp's theory of "ideal" sedimentation tank behavior (Fitch 1958).

Figure 3 shows that if removal of the particles were governed only by the overflow rate and independent of the detention time, the percent solids removal curves should be vertical. If removal of the solids were governed only by the detention time and independent of the overflow rate, the percent solids removal curves should be horizontal. Since the removal curves in Figure 3 are more horizontal, removal of particles is mostly governed by the detention time.

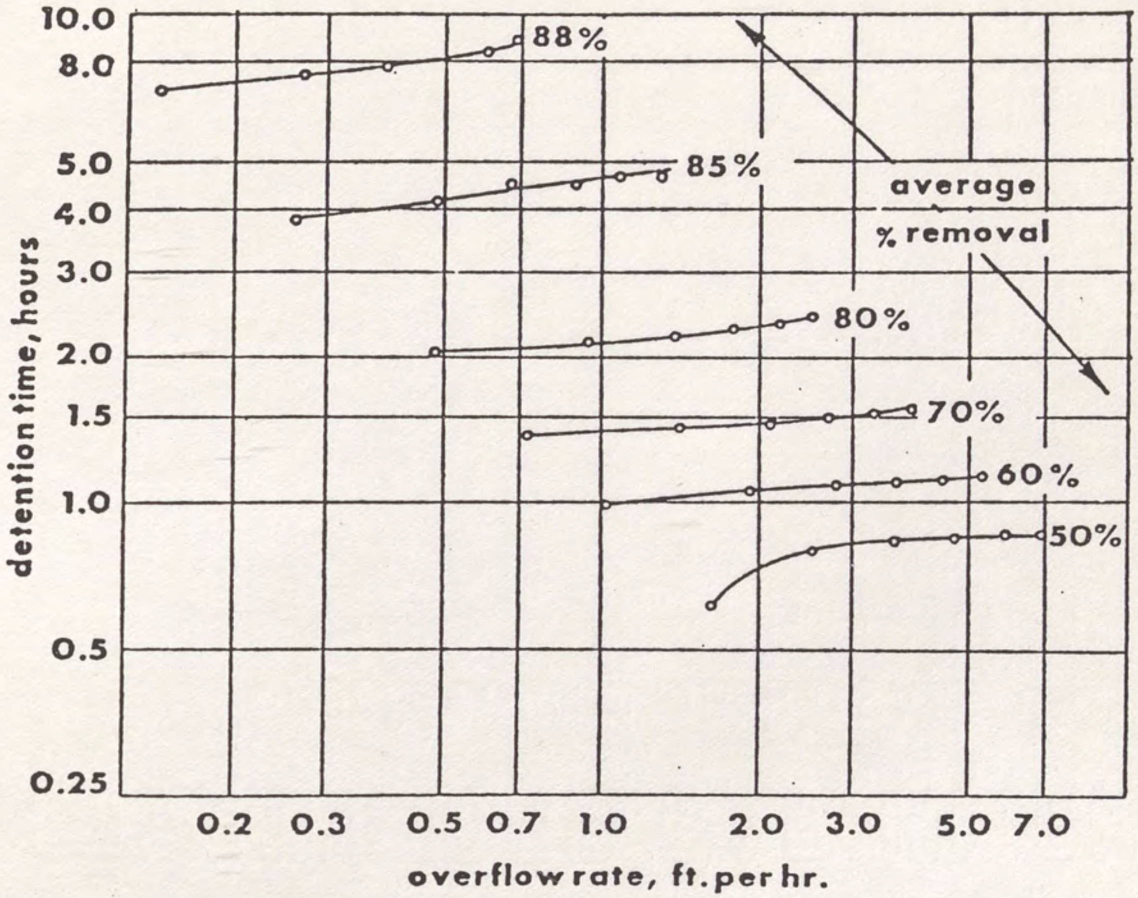

Figure 3. Suspended Solids Removal as a Function of Overflow Rate and Detention Time in Ideal Sedimentation (Fitch 1958).

Field Studies

Cedar Rapids, Iowa

The first full-scale trials of flocculation prior to sedimentation was reported by Fischer and Hillman (1940). The test plant consisted of two clarifiers (50 ft. diameter by 7 ft. side water depth, each having a volumetric capacity of 13,740 ft^3), and a flocculator (48 ft. by 8 ft. water depth) preceding only one of the clarifiers. The flow to the test plant was derived from raw domestic sewage (80 percent) and pre-treated packing house wastes (20 percent). The pre-treatment system for the packing house wastes consisted of grease removal.

The flocculator tank was equipped with four horizontal transverse rows of 6 ft.-6 in. diameter paddles that were run at a constant speed of 3.15 rpm. The results of the six tests are presented in Table 3. The tests verified the effectiveness of utilizing flocculators for removal of suspended solids. In tests number 1, 2, 5 and 6, equal flows were introduced to both flocculator-clarifier combination and conventional clarifier operating side-by-side, to investigate the effect of flocculation on solids removal efficiency. The flocculator-clarifier combination achieved superior suspended solids removal as compared to the conventional system when subjected to identical hydraulic loading conditions. The result from tests number 3 and 4 indicate that flow capacity can be tripled for the flocculator-clarifier to achieve the same solids removal efficiency as the conventional clarifier.

The result of the tests in Table 3 indicate a significant improvement in efficiency of the plant as evaluated by solids removal. It is interesting to note that during tests number 5 and 6, a lower flow rate was introduced to the clarifiers. This condition provided lower overflow rate, hence longer detention times in the clarifier. The consequence of the longer detention time and lower overflow rate

TABLE 3

INCREASE IN SETTLING EFFICIENCY DUE TO PRE-FLOCCULATION AT CEDAR RAPIDS, IOWA

TEST NO.	RAW SEWAGE SUSPENDED SOLIDS (ppm)	INCREASE IN PERCENT REMOVAL DUE TO FLOCCULATION	CLARIFIER DETENTION (hrs)		CLARIFIER OVERFLOW RATE (gal/ft^2-day)		FLOW RATIO
			WITH FLOC.	NO FLOC.	WITH FLOC.	NO FLOC.	$\frac{\text{FLOW TO FLOC.-CLARIFIER}}{\text{FLOW TO CLARIFIER}}$
1	258	19.8	1.9	1.9	662	662	1.0
2	208	36.6	1.9	1.9	662	662	1.0
3	280	6.9	1.4	2.9	918	407	2.35
4	271	7.0	1.25	3.8	1040	306	3.33
5	266	50.0	3.8	3.8	306	306	1.0
6	257	24.4	2.5	2.5	510	510	1.0

SOURCE: Fischer and Hillman (1940)

at the flocculation clarifier was a significant increase in the effectiveness of the flocculator with respect to solids removal. Because the clarifier dimensions were fixed, it is impossible to distinguish between the effects of the lower overflow rate and the longer detention time in solid removal efficiency.

Emscher Mouth Treatment Plant

In 1955, a full-scale pilot plant was constructed to treat Emscher River water. Emscher water receives the sewage and waste of 2.5 million people, numerous coal mines, several large-scale refineries and other chemical plants. The significance of systematic flocculation by agitators as an improvement of secondary sedimentation efficiency was investigated in an activated sludge process. The following operating conditions were tested in parallel and/or successively in the activated sludge secondary sedimentation tanks (Knop 1966):

1. Secondary sedimentation without flocculation by agitation.

2. Secondary sedimentation with flocculation by agitation of 12 minutes duration in which the flocculation chamber was separated from the subsequent secondary sedimentation.

3. Secondary sedimentation with flocculation by agitation for 12 minutes where the agitator is located in the inlet zone of the secondary sedimentation basin.

The results from these tests are shown in Figure 4. The efficiency of the plant is characterized by effluent transparency. Sedimentation with flocculation in the inlet zone shows the highest

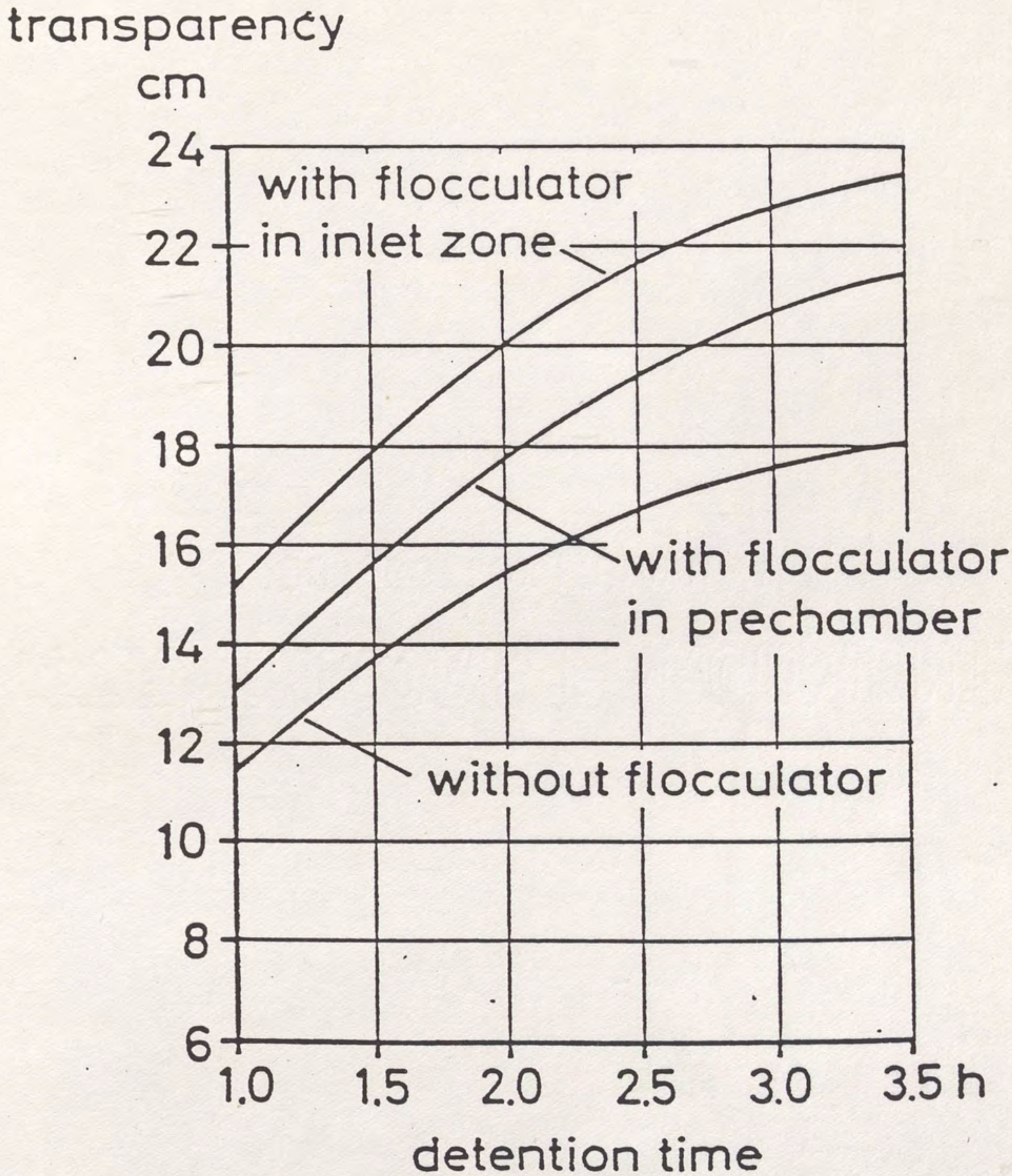

Figure 4. Relationship Between Effluent Transparency and Detention Time in Final Sedimentation Tank (Knop 1966).

transparency, thus the greatest efficiency. This special arrangement avoids any possible floc break-up during transfer of the mixed liquor from the separate flocculation chamber to the sedimentation tank. It is interesting to note that the same solids removal can be achieved at 1.5 hours detention time in the clarifier with inlet zone flocculation as with 3.5 hours detention time in the clarifier without the flocculator. The option of lower detention time in the sedimentation tank for the achievement of the required solid removal may save considerable cost for the sedimentation tank due to a smaller size.

Corvallis, Oregon

In 1973, the Corvallis, Oregon, Wastewater Treatment Plant was a conventional trickling filter process with effluent BOD and suspended solids of 20-50 mg/l. Effluent quality standards were upgraded to maximum BOD and suspended solids concentrations of 10 mg/l (Norris et al. 1982). These effluent quality standards were impossible to achieve without addition of tertiary treatment by means of filtration or chemical addition to assist flocculation. To utilize the existing facility, the engineers decided to couple the existing trickling filter (TF) with an activated sludge process (Norris et al. 1982). Modification of the secondary clarifiers receiving mixed liquor was provided by construction of flocculation clarifiers. The modified secondary clarifier design values and general design criteria based on design guidelines by the Joint Committee of the American Society of Civil Engineers and the Water Pollution Control Federation (1977), are noted in Table 4. The Corvallis clarifier depths exceed the general design criteria for the specified diameter.

TABLE 4

CLARIFIER DESIGN CRITERIA

SOURCE	DEPTH (m)	DIAMETER (m)
WPCF Design Guidelines	4.3	30-43
Corvallis Wastewater Treatment Plant	5.5	35.1

SOURCE: Joint Committee of the American Society of Civil Engineers and the Water Pollution Control Federation (1977) and Norris et al. (1982)

The feed well of the secondary clarifier was modified to provide solids contact for the mixed liquor. The feed well has a 12 ft. depth, 44 ft. diameter and 20 minutes detention time at design flow with 100 percent return sludge flow.

The operation of the modified plant at Corvallis started in March of 1978 and successfully met the requirements of the discharge permit from the first day of operation. In January 1979, the activated sludge process was shut down and the trickling filter effluent was by-passed directly to the secondary clarifiers, as shown in Figure 5. At this time, the only significant changes from the original plant was the new flocculator-clarifier and recirculation of the sludge to the aerated return sludge chamber.

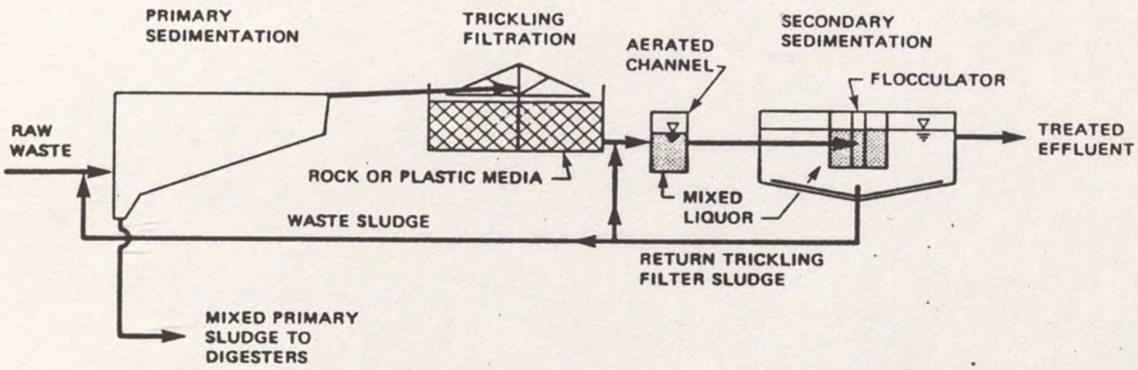

Figure 5. Trickling Filter/Solid Contact Process (Norris et al. 1982).

From January 1979 through May 15, 1979, the modified plant was operated only with trickling filters; operating data are shown in Figure 6. The modified plant exhibited superior performance when compared to the conventional trickling filter operation. The new process was adopted for operation and has been designated as the trickling filter/solid contact process (TF/SC) (Norris et al. 1982).

The new process (TF/SC), with the recirculation of the return sludge and the solids contact clarifier, contributed significantly to the success of the operation. The return sludge from the secondary clarifier is mixed with trickling filter effluent at the aerated contact channel to provide a slurry which enhances solids contact. The mildly stirred environment of an enlarged feed well of the clarifier may also create an opportunity for agglomeration of fine particles on the surface of heavy flocs, thus increasing the sedimentation efficiency.

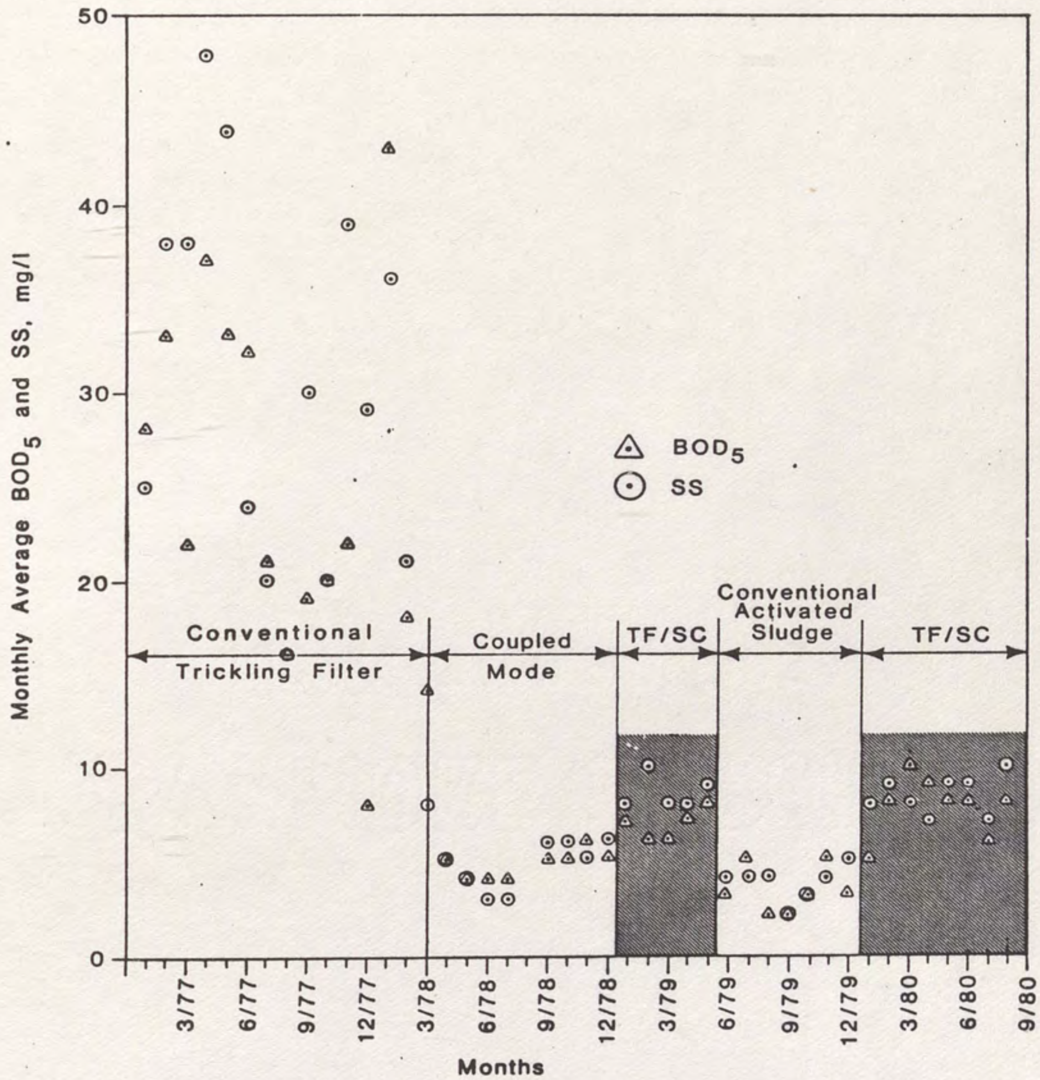

Figure 6. Effluent BOD_5 and Suspended Solids (SS) Concentration, January 1977 - August 1980 (Norris et al. 1982).

The significance of the additional solids contact in improvement of the secondary clarifier performance can be explained by the following three consecutive settleability tests. In each test, the samples of 5 gallons were collected carefully from different points in the plant, as shown in Figure 7. Quiescent settling was provided for 30 minutes before the supernatant was siphoned off and tested for suspended solids. The results from these settleability tests are plotted in Figure 8.

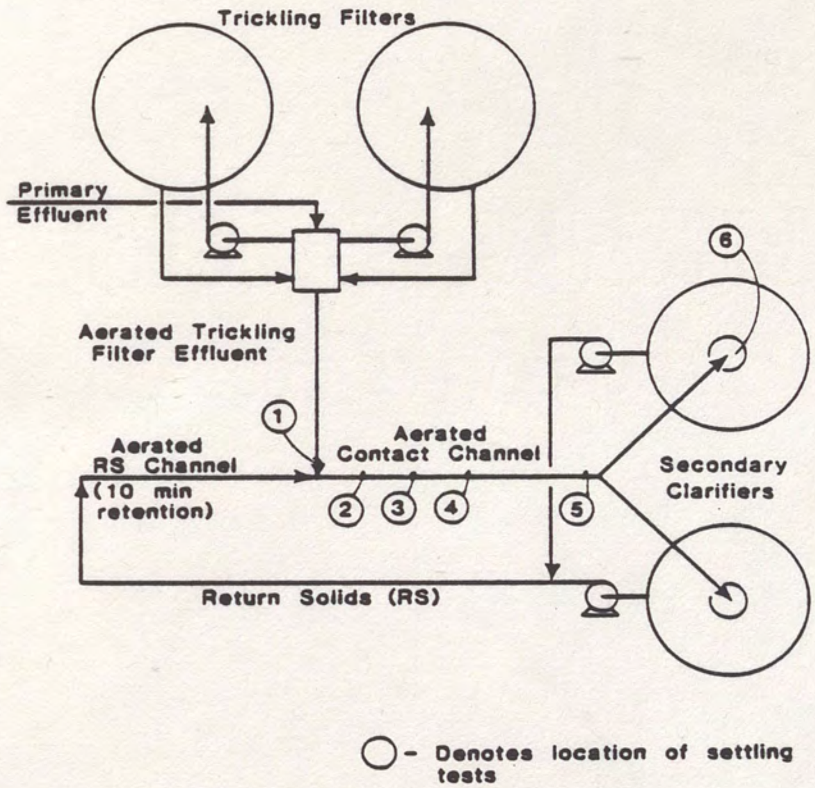

Figure 7. Schematic Location of Settleability Tests (Norris et al. 1982).

Figure 8 shows a poor settleability for the sample taken at point 1 which consisted only of trickling filter effluent; the suspended solid concentration is in the range of 44 to 66 mg/l. For the three

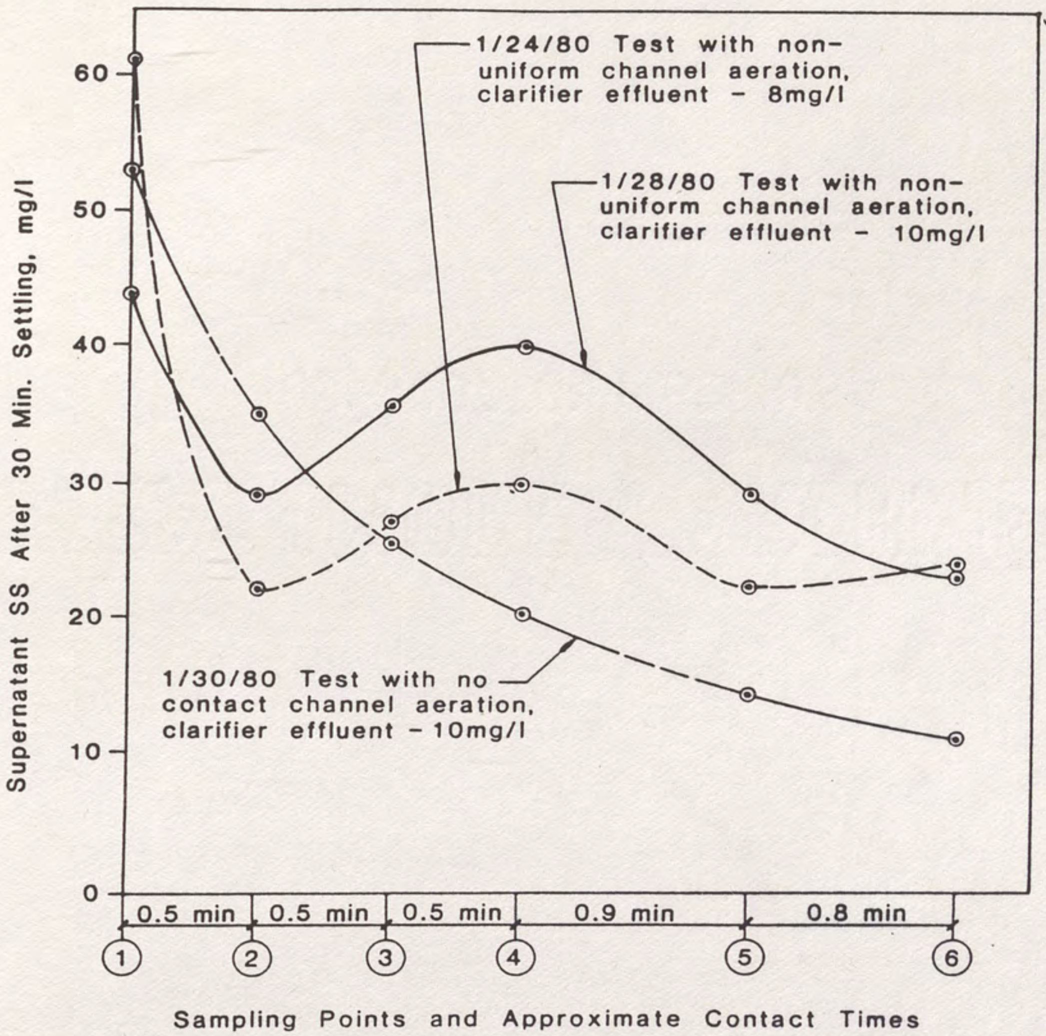

Figure 8. Effect of Solids Contact on Settleability, Winter Data (Norris et al. 1982).

consecutive tests, there is a sharp decline in supernatant suspended solids at point 2 where aerated return sludge was mixed with trickling effluent for 30 seconds. The first two settleability tests indicate an increase in suspended solids as the slurry moved through the aerated contact channel for 1 minute and 30 seconds, corresponding to the data taken from points 3 and 4. However, a decline in concentration in suspended solids is observed at points 5 and 6, as the slurry moves away from the aerated channel towards the feed well of the clarifier. The changes in suspended solids concentration from points 2 to 6, as mentioned above and also shown by the shape of the curves in Figure 8, indicate a strong possibility of floc break-up due to the aeration process of the contact channel. Since the third settleability test was run while the aeration system was shut down, the data from this test indicate a continuous decrease in suspended solids from the point where the return sludge is mixed with trickling filter effluent. From the observation of the data above, one could conclude that air input to the contact channel at Corvallis plant exceeded the optimum amount for mixing and flocculation (Norris et al. 1982).

Regardless of the poor settleability results from tests 1 and 2, when compared with test 3, the secondary clarifier effluent from all three tests showed suspended solids of 10 mg/l or less. The equal effluent quality from the three tests mentioned above demonstrate the fact that broken flocs, as a consequence of the aeration contact channel, had an opportunity to reagglomerate in the flocculator feed well. The long detention time (20 minutes) and the gentle hydraulic turbulence in the feed well of the clarifier made it possible for small particles to conjoin, and also be trapped by larger flocs. This flocculation process played a significant role in the improvement of the secondary clarifier for achievement of high solids removal at the Corvallis plant.

Current Practice

The most important function of the clarifier feed well has been recognized as an energy dissipator (Fitch and Lutz 1960, EIMCO 1984 and Stukenberg et al. 1983). Slurry enters the clarifier through the feed well as a submerged waterfall which carries a considerable amount of kinetic energy. The input energy of the influent is dissipated as a hydraulic loss which causes the turbulence (Sawyer 1956). The turbulence must be decayed in order to prevent disturbance of the sludge blanket. In order for the feed well to serve as an energy dissipator, its diameter should not be less than 20% of the clarifier diameter (Joint Committee of the ASCE/WPCF 1977).

One equipment manufacturer (EIMCO 1984) reports a range in the feed well diameter from 22% to 25% of the clarifier diameter. The standard clarifier dimensions for this manufacturer is summarized in Table 5. The particular clarifier in this table is a standard clarifier with a center feed and blade arrangement to scrape sludge toward the center of the tank.

TABLE 5

STANDARD FEED WELL DIMENSIONS

TANK DIAMETER (feet)	FEED WELL DIAMETER (feet)	FEED WELL DEPTH (feet)	VOLUMETRIC CAPACITY (ft^3)	HYDRAULIC RESIDENCE TIME* (minutes)
30 - 35	8	3.5	176	3.12
40 - 45	10	3.5	276	2.82
50 - 60	12	3.5	396	2.42
65 - 80	16	3.5	704	2.43
85 - 100	24	3.5	1584	3.21

* The hydraulic residence time was calculated assuming an overflow rate of 520 gal/day-ft^2 at 45% recycle flow. The residence time is based on the total flow entering the feed well.

SOURCE: EIMCO (1984)

As a consequence of the turbulent environment of the aeration basin, a high level of dispersed particles would be expected in the mixed liquor. Therefore, physical conditioning of the particles (flocculation) may be needed prior to or during sedimentation. The flocculation process brings the small particles in contact with each other to form larger ones, and hence improve the settling of the particles. The data in Table 5 indicate a hydraulic detention time of less than four minutes in the feed well. The limited detention time suggests that the flocculation in the center well may not be optimal.

In a conventional clarifier, flocculation may take place in the feed well, clear zone or the sludge blanket of the clarifier. Because sludge separation and blanket formation occur very rapidly, most of the opportunities for flocculation are in the clarifier center well (Parker 1983).

Since the 3 to 4 minutes detention time in the center well of the conventional clarifier may not be sufficient for flocculation, modification of the clarifier to provide an enlarged feed well must be considered. The larger detention time provided in the enlarged feed well promotes the flocculation process to improve the settling efficiency.

Summary of Literature Review

Overflow rate and detention time have been considered as design criteria for final clarifiers. There is, however, a disagreement among researchers over the level of significance of these criteria in solids removal efficiency of final clarifier.

In a fixed dimension clarifier, the overflow rate and detention time are interrelated. An increase in overflow rate is associated with a decrease in detention time and vice versa. Hence, it is impossible to distinguish between the effects of these two criteria on suspended solids removal. Detention time can be controlled by variation in the clarifier depth at constant overflow rate. Longer detention times are achieved in deeper clarifiers. Among most environmental engineering practitioners, the overflow rate is recognized as the key factor influencing the suspended solids removal. The depth of the clarifier has been neglected, which is probably due to the fact that the engineers have not fully recognized the flocculent characteristics of biological sludges. In spite of minor differences between sludge characteristics, flocculation has been documented to improve the removal of particles in the final clarifier for trickling filter and activated sludge slurries.

Due to the turbulent environment in activated sludge aeration basins, floc break-up occurs. Therefore, additional flocculation of the mixed liquor has been considered subsequent to aeration. Several field studies have been conducted to provide flocculation prior to or during sedimentation to determine the effect of flocculation on the suspended solids removal efficiency.

In 1940, the first full-scale field study to investigate the effect of flocculation on removal of suspended solids was conducted by Fischer and Hillman. In their experiment, two identical clarifiers were operated side-by-side. A flocculator preceded one of the clarifiers. The results from this experiment indicated that the clarifier preceded by the flocculator had an increased removal of suspended solids of up to 50%.

Norris et al. (1982) reported the success of flocculation in improving the effluent quality of the Corvallis, Oregon, Wastewater Treatment Plant. Flocculation was provided in two locations in the plant. At one location, trickling filter sludge from the secondary clarifier was recycled and mixed with trickling filter effluent in an aerated contact channel immediately upstream from the clarifier. At the second location, the mixture was then introduced to a modified clarifier. The clarifier was deeper than standard and had an enlarged feed well with 20 minutes detention time. This extra detention time provided an opportunity for dispersed solids to contact with flocs and enhance the flocculation process. The entire process using a trickling filter with a solids contact unit was termed the Trickling Filter/Solid Contact process (TF/SC). The effluent suspended solids prior to the installation of the solid contact process were 20 mg/l. After the installation of the solids contact process, the effluent solids were reduced to less than 10 mg/l.

CHAPTER III

RESEARCH OBJECTIVES

The flocculation process has been documented to increase the settling velocities of particles and, therefore, enhance gravity sedimentation processes. Separate flocculation has been investigated with success to improve solids removal efficiency of final clarifiers. Flocculation within the feed well is considered to improve clarifier performance.

In conventional final clarifiers, opportunities for flocculation are provided in the feed well and in the sludge blanket. Typical detention times in the feed well are 3 to 4 minutes. In addition, sludge blanket formation and sludge separation occur rather rapidly. Hence, not all the beneficial factors attributed to flocculation may be exploited.

In some field studies, the clarifier inlet zone has been utilized successfully for solids contact to promote flocculation. As a consequence, the effluent suspended solids of the final clarifier has been reduced significantly. In the Corvallis, Oregon, Wastewater Treatment Plant, a detention time of 20 minutes in the feed well of a modified final clarifier was provided. The relatively long detention time of 20 minutes was reported as the significant factor in reduction of effluent suspended solids from 20 mg/l to less than 10 mg/l (Norris et al. 1982).

The purpose of this research is to experimentally evaluate the effect of providing additional opportunity for flocculation/solids contact for activated sludge mixed liquor in the feed well of a clarifier. Control of the flocculation process is exercised by varying the feed well diameter to provide the desired contact period.

CHAPTER IV

MATERIALS AND METHODS

Equipment

Replicate pilot scale continuous clarifiers with overflow rates of 400 gpd/ft^2 and 75% recycle were employed for the research. Identical units were developed, as described in Table 6 and Figure 9. The inlet structure for each clarifier was a feed well which was suspended 3.28 ft (1 m) below the clarifier surface. Underflow was withdrawn through a ½-inch opening which was located 3.25 inches from the bottom of the clarifier. The clarifier feed was pumped from a 150-gallon aerated holding tank. Flow in and out of the clarifier was pumped through a ¼-inch diameter plastic tube. The characteristics of the pumps are listed in Table 7.

TABLE 6

CLARIFIER DESIGN PARAMETERS

PARAMETER	VALUE
Overflow Rate	400 gpd/ft^2
Percent Recycle	75%
Clarifier Depth	9.84 ft
Clarifier Diameter	8 inches

TABLE 7

CHARACTERISTICS AND APPLICATIONS OF PUMPS

TYPE OF FLOW	APPLICABLE PUMP	CAPACITY	MODEL NUMBER	BRAND NAME
Activated sludge into holding tank	Rotary screen wet pump	1/2 HP	3P569A	Dayton Electric Co.
Activated sludge from holding tank to the clarifier	Positive-Displacement	1/6 HP	7015-21	Cole-Parmer Instrument Co.
Return activated sludge (underflow)	Positive-Displacement	1/6 HP	7015-21	Cole-Parmer Instrument Co.
Effluent (for sampling)	Positive-Displacement	1/6 HP	7016-21	Cole-Parmer Instrument Co.

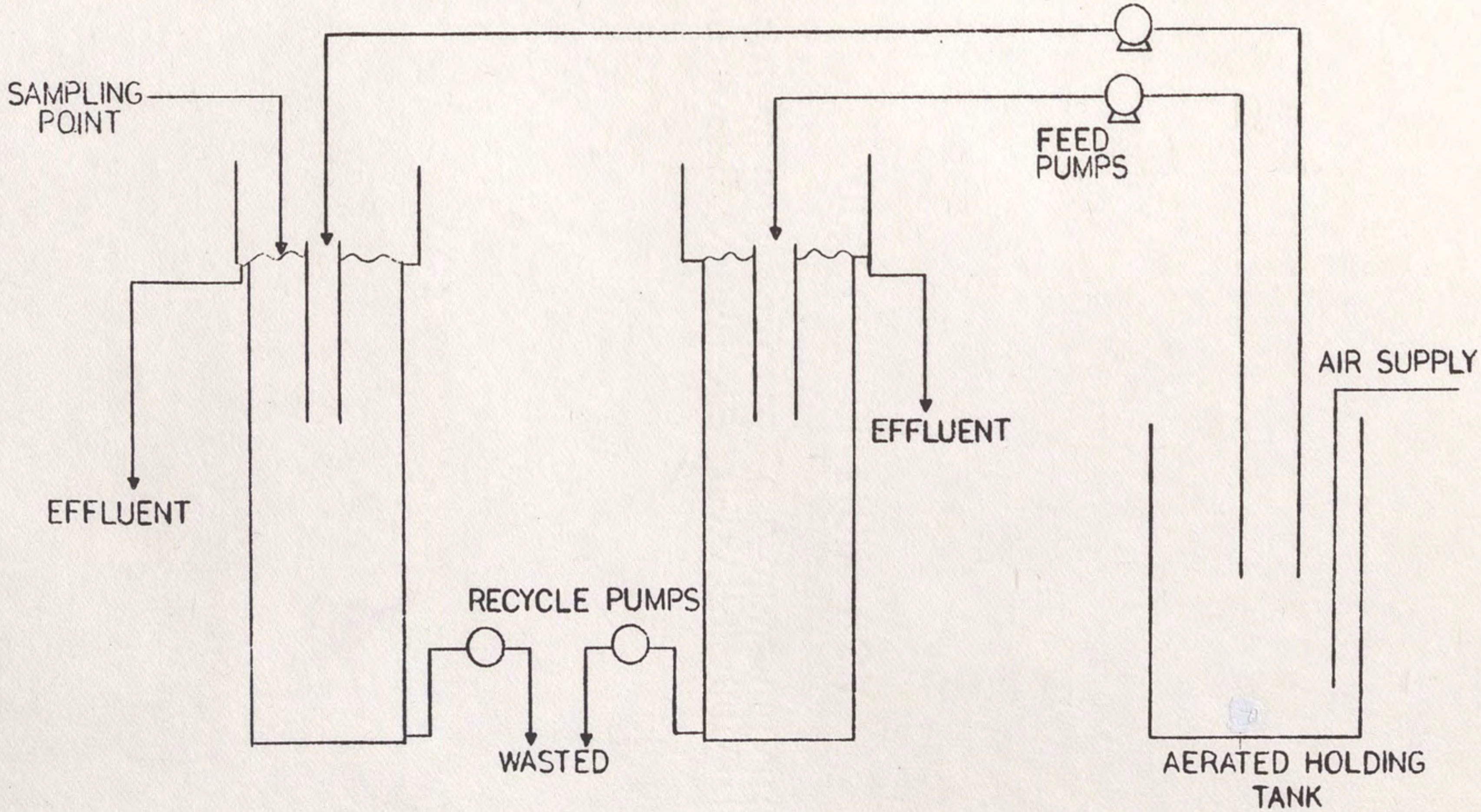

Figure 9. Experimental Apparatus.

A stopwatch and a one-liter graduated cylinder were used for monitoring the flow. The desired level of flow was set with a speed controller and a tachometer.

Activated Sludge Sample

Prior to each experiment, fresh activated sludge was pumped from the aeration basin of the University of Central Florida (UCF) Wastewater Treatment Plant, located 90 feet from the pilot scale clarifiers. This extended aeration activated sludge plant receives mainly domestic waste, and operates with a hydraulic detention time (θh) of 22 hours, mean cell residence time (θc) of 26 days and average mixed liquor suspended solid (MLSS) of 3760 mg/l (Haley 1985).

Throughout the five months of this research, the temperature of the waste was around 22.5^{o}C. The only time the temperature rose to 24.0^{o}C was at the last experiment conducted.

Experimental Procedure

A total of seven experiments were conducted with variable feed well diameters. The experimental design is summarized in Table 8.

As shown in Table 8, the first three experiments were conducted with identical feed well dimensions. These experiments were used to estimate the experimental error variance.

The possibility of time-dependent characteristics of the feed slurry received from the UCF plant could not be eliminated. As mentioned previously, the physical properties and, hence, the settleability characteristic of the slurry flocs are influenced by

TABLE 8

EXPERIMENTAL DESIGN

EXPERIMENT	CLARIFIER A		CLARIFIER B	
	FEED WELL DIAMETER (in)	θh (min)	FEED WELL DIAMETER (in)	θh (min)
1	3	7.11	3	7.11
2	3	7.11	3	7.11
3	3	7.11	3	7.11
4	3	7.11	5.5	23.80
5	5.5	23.80	3	7.11
6	2	3.15	5	19.74
7	5.5	23.80	3	7.11

the operational modes of the aeration basin (e.g., organic loading and dissolved oxygen concentration). Variation of the operational modes over time is not unusual for domestic wastewater treatment plants.

In order to avoid any source of error associated with time-dependent characteristics of the feed slurry, the experiments were conducted in a side-by-side mode. The experiments which were used to estimate the experimental error were genuine replicates with identical feed slurry and clarifier geometry.

The first step in each experiment was to pump the mixed liquor from the aeration basin of the UCF treatment plant into the aerated holding tank. Aeration in the holding tank insured sufficient oxygen transfer to the mixed liquor prior to entering the clarifier. The aeration in the tank also maintained the solids in suspension. The clarifiers were initially filled with tap water. Mixed liquor was then introduced at a feed rate of 244 gal/day.

The most significant source of problems in performing the experiments resulted from clogging in the tubes which directed the feed flow and underflow. The potential complication was avoided by monitoring the flow with a one-liter graduated cylinder and a stopwatch every few minutes and regular adjustment of flowrates.

During each experiment, effluent samples were collected during the first eight hours on an hourly basis. These eight samples were used to verify that steady state was attained after eight hours of operation. From previous work with a similar apparatus, eight hours was reported to be adequate to reach steady state (Dietz 1982 and Margio 1985).

Ten replicate samples were collected at the termination of the experiment to characterize the effluent suspended solids for evaluation of the performance of the clarifiers. All of the samples were preserved by refrigeration at $5^{o}C$ prior to suspended solids analysis. All the suspended solids concentrations were determined within 24 hours of the respective experiments. Three-hundred ml from each of the samples was filtered with a Buchner funnel filtering device through (Whatman GF/C) 1.0 μm glass fiber filters (Standard Methods 1985).

Use of smaller sample sizes is not recommended since the results may not provide a true representation of the effluent concentration. In addition, in each solid analysis, there is a possibility of losing some solids on the walls of the filtering device. This problem would be relatively pronounced in smaller samples.

CHAPTER V

RESULTS AND DISCUSSION

Results

The average values of the ten samples from each clarifier effluent suspended solids taken after an eight-hour period were used for evaluation of the clarifier's performance. These average values from each experiment with corresponding feed well diameters are shown in Table 9. The entire results are included in the Appendix.

TABLE 9

MEAN EFFLUENT SUSPENDED SOLIDS FOR CORRESPONDING FEED WELL DIAMETER

EXPERIMENT	DATE	FEED WELL DIAMETER (inches)	EFFLUENT SUSPENDED SOLIDS (mg/l)	FEED WELL DIAMETER (inches)	EFFLUENT SUSPENDED SOLIDS (mg/l)
1	2/13/85	3	12.42	3	11.53
2	2/24/85	3	7.60	3	8.07
3	3/28/85	3	8.07	3	7.72
4	4/06/85	3	7.70	5.5	8.86
5	4/12/85	5.5	8.67	3	6.62
6	4/30/85	2	6.65	5	8.96
7	6/07/85	5.5	9.81	3	5.57

Due to the feed pump failure of the clarifier during the experiment on 4/12/85, there is limited data available associated with the three inch feed well diameter (five replicates). Therefore, this experiment was repeated on 6/07/85. Two sets of replicate experimental units with feed well diameters of three inches were initially proposed to provide an estimate of the experimental error variance. Since experiment number 1 on 2/13/85 showed high effluent suspended solids relative to experiment number 2 on 2/24/85, a third replicate experiment was undertaken on 3/28/85.

Experiment number 1 on 2/13/85 was conducted a few weeks after a two-week school break at UCF. During this period, the school cafeteria and dormitories were not operating; therefore, a minimal waste quantity was generated. As a result, a low strength waste was received at the UCF treatment plant. During this period, an elevated effluent suspended solids concentration from the plant was observed (Haley 1985). Because of these unusual conditions at the plant, the results from experiment number 1 were used only to estimate the experimental error variance.

In the larger feed well diameters (5 and 5.5 inches), the feed slurry was observed to enter the clarifier as a dilute blanket (Dietz and Keinath 1984). In contrast, the feed slurry of the smaller feed well diameter (2 inches) entered as a submerged waterfall (Sawyer 1956).

In the enlarged feed well diameter, due to auto-flocculation in the feed well, larger floc particles were visually observed, although efforts to determine the particle diameter were not pursued. According to Stoke's Law (equation 4), the settling velocities would increase for the larger particles. One would, therefore, expect better removal efficiencies of the suspended solids for this case. However, this result was not observed in this research.

The available clarification zone was concentric with the feed well in the clarifier. Therefore, any increase in the diameter of the feed well affected the clarification zone by means of reduction in clear zone detention time and available surface area for effective determination of overflow rate. Those factors impaired the beneficial effect of flocculation in the feed well which could have increased the suspended solids removal efficiency of the clarifier.

Overflow Rate and Detention Time

As the feed well diameter was increased from 2 to 5.5 inches, the available area for overflow decreased from 47.12 to 25.61 square inches. The corresponding overflow rate (defined with the effective overflow area) therefore increased from 427 to 757 gal/day. For a fixed dimension clarifier, the detention time is inversely proportional to the overflow rate (equation 15). Therefore, the clarifier detention time decreased as the overflow rate increased. The associated changes in the overflow rates and detention times in the clear zone are shown in Table 10 for the feed well sizes employed in this research.

The hydraulic detention time in the feed well is proportional to the square of the feed well diameter, as shown in equation (18):

TABLE 10

OVERFLOW VELOCITY AND DETENTION TIME
FOR CORRESPONDING FEED WELL DIAMETER

FEED WELL DIAMETER (in)	AREA FOR OVERFLOW* (in^2)	OVERFLOW RATE (gpd/ft^2)	DETENTION TIME IN CLEAR ZONE (min)
2.0	47.12	427	83.0
3.0	43.20	466	76.0
5.0	30.63	657	53.9
5.5	26.51	757	46.6

* Area for Overflow = (area of clarifier) - (area of feed well)

$$\theta h = \frac{V}{Q} \quad (16)$$

$$V = L \times \frac{\pi D^2}{4} \quad (17)$$

$$\theta h = 10.77 \times 10^3 \frac{L \pi D^2}{4Q} \quad (18)$$

where:

10.77×10^3 = conversion factor ($min\text{-}gal/day\text{-}ft^3$)

θh = hydraulic detention time (min)

V = volume of feed well (ft^3)

L = length of feed well (ft)

Q = clarifier inflow (gal/day)

D = diameter of feed well (ft)

Since the clarifier inflow (Q) and the length of the feed well (L) were held constant during the experimental program:

$$\theta h = 113.72\ D^2 \tag{19}$$

Equation (19) shows that the feed well detention time is proportional to the square of the diameter. The data are presented in Figure 10 to illustrate the correlation between clarifier performance and feed well design.

The effective overflow rate was directly related to the square of the feed well diameter, therefore, effluent suspended solids concentration can be expressed as a function of the overflow rate, defined with overflow area, shown in Figure 11.

Discussion

An analysis of variance has been used to analyze the relationship between the independent variables (feed well diameter and overflow rate) and the dependent variable (effluent suspended solids).

A least squares-based regression model was used to determine the model parameter estimates. The general multiple regression model can be stated as follows (McClane et al. 1985):

$$y = Bo = B1*x1 + B2*x2 + \ldots + Bk*xk + e \tag{20}$$

where:

y = dependent variable, effluent suspended solids

xk = independent variable, feed well diameter and/or overflow rate

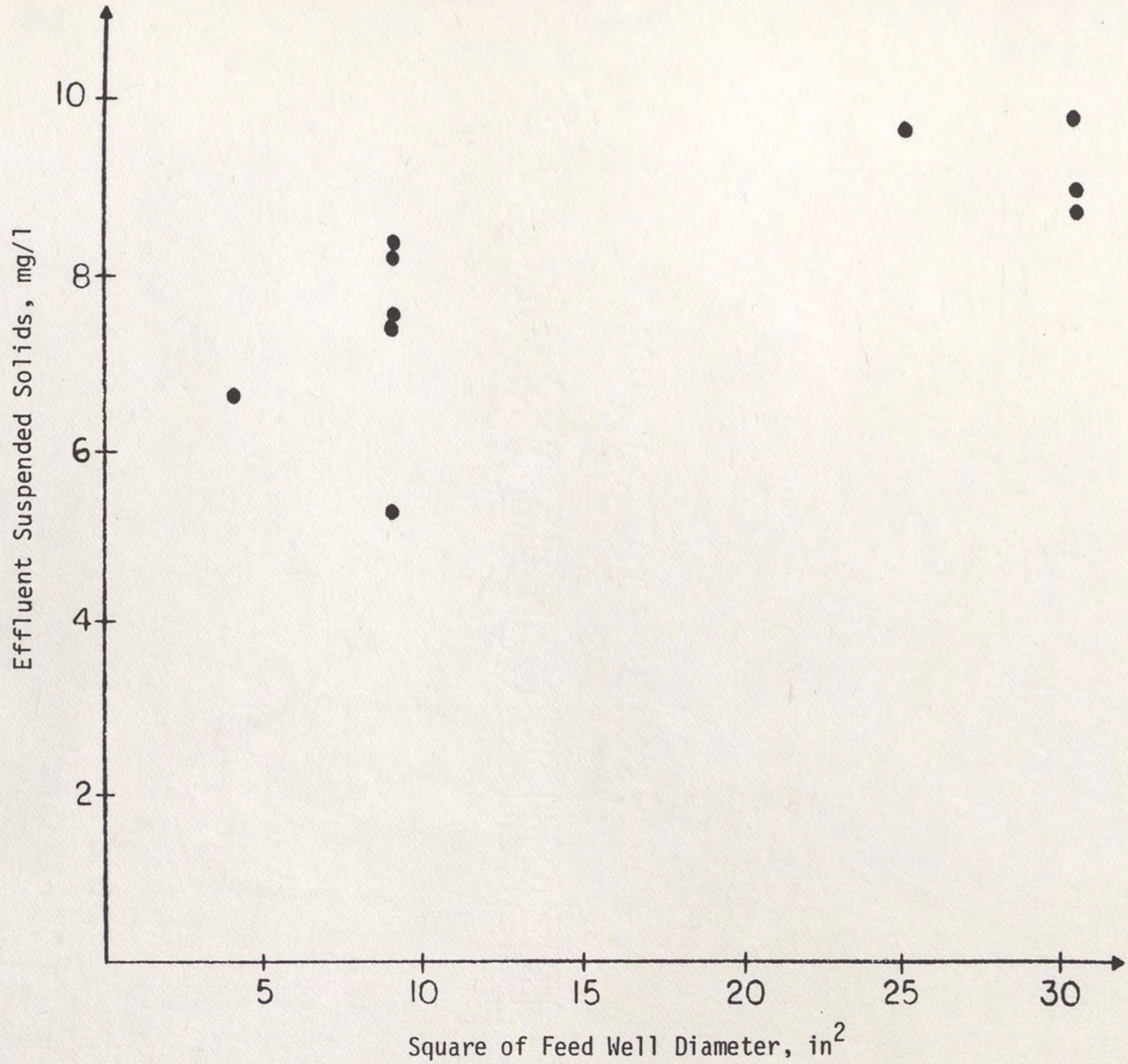

Figure 10. Feed Well Diameter Square versus Effluent Suspended Solids.

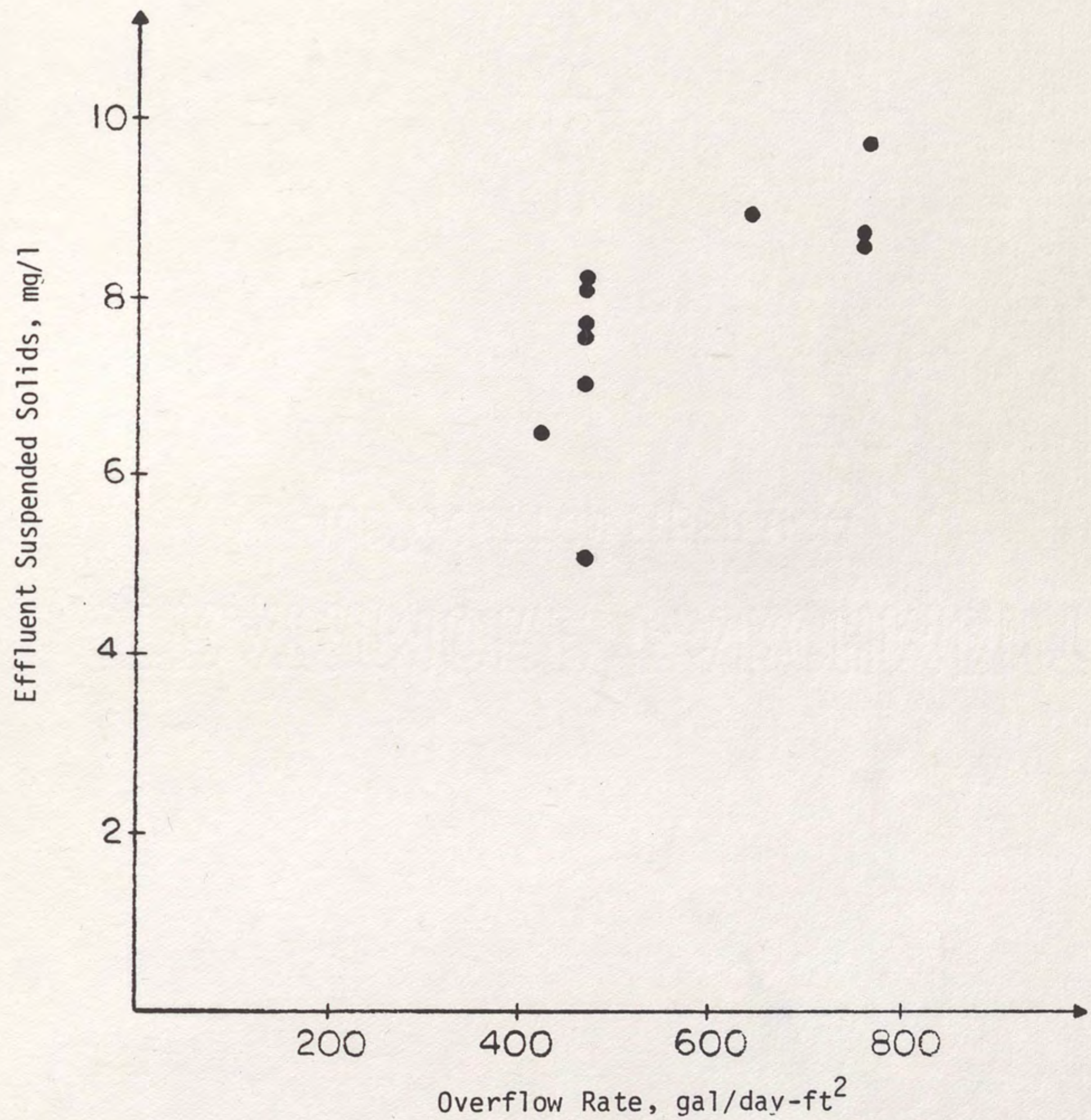

Figure 11. Effective Overflow Rate versus Effluent Suspended Solids.

Bk = model parameter

e = error

The estimates y' and B' of the dependent variable y and parameter B, respectively, can be expressed as follows:

$$y' = B'o + B'1*x1 + \ldots + B'k*xk \qquad (21)$$

where y' is such that $\Sigma(yi - y'i)^2$ is minimized. $\Sigma(yi - y'i)^2$ is called the error sum of the squares, that is:

$$SSE = \Sigma(yi - y'i)^2 \qquad (22)$$

Three sets of replicate experiments were conducted to provide an estimate of the experimental error variance (EMS), as summarized in Table 11. This estimate of the experimental error variance was used to perform an analysis of variance to determine the statistical significance of the research findings.

TABLE 11

EFFLUENT SUSPENDED SOLIDS CONCENTRATION
FROM THREE REPLICATE EXPERIMENTS

EXPERIMENT	FEED WELL DIAMETER (in)	DATE	EFFLUENT CONCENTRATION (mg/l)	
			CLARIFIER A	CLARIFIER B
1	3	2/13/85	12.42	11.53
2	3	2/24/85	7.60	8.07
3	3	3/28/85	8.07	7.72

Using three degrees of freedom (DF), EMS can be computed as follows:

$$\mathrm{EMS} = \frac{\mathrm{SSER}}{\mathrm{DF}} \tag{23}$$

$$= \frac{0.5699}{3}$$

$$= 0.18997 \ \mathrm{mg}^2/\mathrm{l}^2$$

$$\mathrm{SSER} = \sum_{k=1}^{3} \sum_{j=1}^{2} (x_{kj} - \overline{x}_k)^2$$

where:

SSER = sum of squares

$\overline{x}_k$ = mean value for experiments 1, 2 and 3

k = experiments 1, 2 and 3

J_1 = clarifier A

J_2 = clarifier B

Determination of Significance of Feed Well Diameter

An analysis of variance procedure was used for hypothesis testing to determine the significance of the change in the feed well diameter with respect to effluent suspended solids concentration. The procedure involves a comparison of the sum of squared error (SSE) resulting from application of the three different models given in equations (24) through (26).

$$SS = Bo \tag{24}$$

$$SS = Bo + B1*DIASQ \tag{25}$$

$$SS = Bo + B1*DIASQ + B2*DIASQ^2 \tag{26}$$

where:

SS = effluent suspended solids, mg/l

DIASQ = squared feed well diameter, in^2

The basic model specified in equation (24) suggests the dependent variable SS to be independent of the diameter. The second model in equation (24) suggests that there is a linear relationship between SS and DIASQ. The last model given in equation (25) suggests a quadratic relationship between SS and DIASQ.

The significance of the reduction in SSE as a result of incorporating the terms DIASQ and $DIASQ^2$ was investigated by applying hypothesis testing. In these tests, the parameters B1 and B2 corresponding to equations (25) and (26) are sequentially set equal to zero. Two different analyses of variance were conducted to test the hypothesis that B1 equals zero and B2 equals zero, respectively. The null hypothesis given in tables 13 and 14 are tested as follows (Neter and Wasserman 1974):

$$F = \frac{\text{hypothesis mean square}}{\text{EMS}} \tag{27}$$

where:

$$\text{hypothesis mean square} = \frac{\text{hypothesis sum of square}}{\text{hypothesis degree of freedom}}$$

The sum of squared error (SSE) associated with each model is summarized in Table 12. The analyses of variance to identify the significance of DIASQ and $DIASQ^2$ are summarized in tables 13 and 14, respectively.

TABLE 12

SUM OF THE SQUARED ERROR FOR SPECIFIED MODEL

MODEL	EQUATION	SSE
1	24	13.410
2	25	5.356
3	26	5.168

The analysis of variance indicates a statistically significant influence of the feed well diameter on the effluent suspended solids. The second order term contributes no improvement to the model. Hence, a quadratic relationship is not suggested. Therefore, in the data range reported, the best suspended solids removal was achieved with a feed well diameter of two inches. Considering the results from the analysis of variance, the proper model for relating the feed well diameter to effluent suspended solids is:

$$SS = 6.630 + 0.085\ DIASQ \tag{28}$$

TABLE 13

ANALYSIS OF VARIANCE TO DETERMINE THE SIGNIFICANCE OF DIASQ

Null Hypothesis:	B1 = 0
Hypothesis Sum of Squares:	13.410 - 5.356 = 8.054
Hypothesis Degree of Freedom:	1
Hypothesis Mean Square:	8.054/1 = 8.054
Error Mean Square:	0.18997
Estimated Parameters:	Bo = 6.630; B1 = 0.085
F (calculated):	8.054/0.18997 = 42.397
F (0.05, 1, 3):	10.13
Conclusion:	Since F (calculated) > F (0.05), there is sufficient evidence to reject the null hypothesis. The feed well diameter has a significant effect on performance.

TABLE 14

ANALYSIS OF VARIANCE TO DETERMINE THE SIGNIFICANCE OF $DIASQ^2$

Null Hypothesis:	$B2 = 0$
Hypothesis Sum of Squares:	5.356 - 5.168 = 0.188
Hypothesis Degree of Freedom:	1
Hypothesis Mean Square:	0.188/1 = 0.188
Error Mean Square:	0.18997
Estimated Parameters:	Bo = 5.900; B1 = 0.200; B2 = -0.003
F (calculated):	0.188/0.18997 = 0.989
F (0.05, 1, 3):	10.13
Conclusion:	Since F (calculated) $<$ F (0.05), there is insufficient evidence to reject the null hypothesis. This effect is not shown to be significant.

SS and DIASQ are expressed in mg/l and $inches^2$, respectively. This simple two-parameter linear model suggests that suspended solids increase with increasing the feed well diameter.

Determination of Significance of Overflow Rate

As mentioned previously, the feed well diameter and the overflow rate are interdependent variables. Since enlargement of the feed well increased the effective overflow rate significantly, it would be relevant to consider the significance of overflow rate on effluent quality. For this purpose, the analysis of variance was conducted in the same manner as mentioned earlier.

The following three models are proposed:

$$SS = Bo \tag{29}$$

$$SS = Bo + B1*(\overline{ORA}) \tag{30}$$

$$SS = Bo + B1*(\overline{ORA}) + B2*(\overline{ORA})^2 \tag{31}$$

where:

SS	= effluent suspended solids, mg/l
$\overline{ORA}$	= overflow rate defined with the overflow area, $gal/day\text{-}ft^2$
Bo, B1 and B2	= parameters to be determined

TABLE 15

SUM OF THE SQUARED ERROR (SSE) FOR SPECIFIED MODEL

MODEL	EQUATION	SSE
1	29	13.410
2	30	5.606
3	31	5.217

The conclusion based on the analysis of variance given in Table 16 suggests a two-parameter linear model. The model defines the relationship between the overflow rate and the effluent suspended solids as a straight line:

$$SS = 4.449 + 0.0063*(\overline{ORA}) \quad (32)$$

SS and $\overline{ORA}$ are defined as mg/l and gal/day-ft^2, respectively. The model indicates that the effluent suspended solids increase with increasing overflow rate.

Based on the analysis of variance in Table 17, the possibility of a quadratic relationship between effluent suspended solids and overflow rate in the data range of 426.8 to 756.6 gal/day-ft^2 is limited.

The enlargement of the feed well diameter causes an increase in the overflow rate by reducing the available area for overflow. Due to the inverse relationship between overflow rate and detention time,

TABLE 16

ANALYSIS OF VARIANCE TO DETERMINE THE SIGNIFICANCE OF $\overline{\text{ORA}}$

Null Hypothesis:	B1 = 0
Hypothesis Sum of Squares:	13.410 - 5.606 = 7.804
Hypothesis Degree of Freedom:	1
Hypothesis Mean Square:	7.804/1 = 7.804
Error Mean Square:	0.18997
Estimated Parameters:	Bo = 4.449; B1 = 0.006
F (calculated):	7.804/0.18997 = 41.080
F (0.05, 1, 3):	10.13
Conclusion:	Since F (calculated) > F (0.05), there is sufficient evidence to reject the null hypothesis. The overflow rate has a significant effect on performance.

TABLE 17

ANALYSIS OF VARIANCE TO DETERMINE THE SIGNIFICANCE OF $(\overline{ORA})^2$

Null Hypothesis:	B2 = 0
Hypothesis Sum of Squares:	5.606 - 5.217 = 0.389
Hypothesis Degree of Freedom:	1
Hypothesis Mean Square:	0.389/1 = 0.389
Error Mean Square:	0.18997
Estimated Parameters:	Bo = -5.515; B1 = 0.043, B2 = -2.908
F (calculated):	0.389/0.18997 = 2.048
F (0.05, 1, 3):	10.13
Conclusion:	Since F (calculated) < F (0.05), there is insufficient evidence to reject the null hypothesis. This effect is not shown to be significant.

an increase in overflow rate yields a lower detention time. Therefore, decreasing the detention time increases the effluent suspended solids which is consistent with the results reported by Dietz and Keinath (1984).

CHAPTER VI

SUMMARY AND CONCLUSIONS

Floc formation of the mixed liquor in an activated sludge process occurs in the aeration basin. The aeration process serves the dual function of oxygen transfer and suspension of solids. The conventional design of aeration facilities results in a high velocity gradient (G) which creates a highly turbulent environment in the basin. A consequence of the turbulence in the basin is floc break-up and dispersal of particles.

Due to the floc break-up phenomenon in the aeration basin, physical conditioning of the floc should be considered prior to or during sedimentation in the final clarifier. The flocculation process is an agglomeration of dispersed particles on the surface of flocs. The dispersed particles could be particles which were detached from the flocs in the aeration basin or which were originally present in the mixed liquor and were not trapped by the floc. As a result of flocculation, larger particles are formed which enhance the settling velocities of the particles. This process has been documented to increase the suspended solids removal efficiency.

Previous field studies have successfully utilized the flocculation process for solids removal in the final clarifier. In some studies, a separate flocculator unit was provided before the final clarifier. In other studies, an enlarged feed well with additional detention time was used as a flocculator. In either case, the suspended solids removal efficiency of the final clarifier was increased significantly.

This research investigated the potential benefit of auto-flocculation for activated sludge mixed liquor in the feed well of the clarifier. In order to enhance the flocculation process in the feed well, the diameter of the feed well was enlarged. Since the clarification zone was concentric with the feed well, any increase in the feed well diameter resulted in a smaller clarification zone. Higher effective overflow rates and shorter clear zone detention times are associated with a smaller clarification zone. Considering the fixed dimensions of the clarifier (i.e., clarifier diameter and feed well submergence), it may not be possible to distinguish clearly between the effect of overflow rate and detention time on the elevated effluent suspended solids associated with larger feed wells.

The enlarged feed well provided additional detention time in the feed well for solids contact. Larger particles were visually observed in the clear zone of the clarifier. Therefore, the main purpose of additional detention time was already served in the enlarged feed well. The floc particles leaving the feed well settled more as discrete particles which have no more tendency to cohere. Hence, the removal of these particles was governed mostly by the effective overflow rate rather than by detention time. The settling velocities of these particles were smaller than the elevated effective overflow rate, resulting in an increase in effluent suspended solids concentration.

Based on the findings and observations in this research for a fixed-dimension clarifier, an enlarged flocculator feed well for a better suspended solids removal is not recommended. However, flocculation in the feed well can be beneficial in suspended solids removal if no compromise is made between an enlarged flocculator feed well and the available overflow area. This modification would require adjustment of feed well length (rather than diameter) to achieve additional feed well detention.

In the data range reported in this research, the minimum feed well diameter (25 percent of clarifier diameter) was found to achieve the best result with respect to effluent suspended solids. Smaller feed well diameters were not employed because the energy dissipation function of feed well could have been impaired. The optimum configuration reported in this research appears to be consistent with current practice.

Recommendations

In this research, the effect of flocculation in an enlarged feed well on solids removal efficiency of a clarifier was investigated. The feed well was concentric with the clear zone. Therefore, any increase in the feed well resulted in a decrease in the area available for overflow and detention time in the clear zone. The results from this research indicate that effluent suspended solids concentration increases with increases in the feed well diameter. Any possible benefit associated with the flocculation in the enlarged feed well was negated by the decrease in the associated detention time and the corresponding increase in the overflow rate.

Further studies are suggested in order to investigate the effect of the flocculation in the enlarged feed well without compromising the detention time in the clear zone and the overflow rate. Using the same apparatus as used in this research, a lower inflow can be introduced through an enlarged feed well. This inflow must be controlled to achieve a constant detention time and a constant effective overflow rate ($\overline{ORA}$) in the clarifier.

APPENDIX

TABLE 18

STEADY-STATE REPLICATE ANALYSES
(2/13/85)

CLARIFIER A WITH FEED WELL DIAMETER OF 3 INCHES (FEED CONCENTRATION = 3430 mg/l)		CLARIFIER B WITH FEED WELL DIAMETER OF 3 INCHES (FEED CONCENTRATION = 3430 mg/l)	
EFFLUENT SUSPENDED SOLIDS (mg/l)	UNDERFLOW CONCENTRATION (mg/l)	EFFLUENT SUSPENDED SOLIDS (mg/l)	UNDERFLOW CONCENTRATION (mg/l)
13.88	5510	12.22	6875
14.50	6970	15.20	6675
10.80	7350	10.50	5730
11.60	5690	10.00	5830
8.66	5800	7.20	5940
11.50	6800	14.60	6410
14.40		10.05	
13.34		12.00	
13.10		12.00	
$\bar{x}$ = 12.42	$\bar{x}$ = 6350	$\bar{x}$ = 11.53	$\bar{x}$ = 6243.3
s = 1.94	s = 780	s = 2.45	s = 477.4
confidence interval ($\alpha = 0.05$) = $10.91 < \mu < 13.93$	confidence interval ($\alpha = 0.05$) = $5540 < \mu < 7170$	confidence interval ($\alpha = 0.05$) = $9.64 < \mu < 13.42$	confidence interval ($\alpha = 0.05$) = $5742 < \mu < 6744$

TABLE 19
STEADY-STATE REPLICATE ANALYSES
(2/24/85)

CLARIFIER A WITH FEED WELL DIAMETER OF 3 INCHES (FEED CONCENTRATION = 3485 mg/l)		CLARIFIER B WITH FEED WELL DIAMETER OF 3 INCHES (FEED CONCENTRATION = 3485 mg/l)	
EFFLUENT SUSPENDED SOLIDS (mg/l)	UNDERFLOW CONCENTRATION (mg/l)	EFFLUENT SUSPENDED SOLIDS (mg/l)	UNDERFLOW CONCENTRATION (mg/l)
11.00	7029	11.80	7120
8.40	7050	9.41	6946
5.60	7100	6.30	7320
7.20	7240	6.40	7400
6.10	7650	6.40	7670
8.16	8130	8.80	7900
7.30		9.60	
7.20		8.55	
8.00		8.24	
7.04		5.20	
$\overline{x}$ = 7.60	$\overline{x}$ = 7366	$\overline{x}$ = 8.07	$\overline{x}$ = 7392
s = 1.48	s = 439	s = 1.99	s = 350
confidence interval (α = 0.05) = $6.613 < \mu < 8.59$	confidence interval (α = 0.05) = $6905 < \mu < 7827$	confidence interval (α = 0.05) = $6.82 < \mu < 9.33$	confidence interval (α = 0.05) = $7025 < \mu < 7760$

TABLE 20

STEADY-STATE REPLICATE ANALYSES
(3/28/85)

CLARIFIER A WITH FEED WELL DIAMETER OF 3 INCHES (FEED CONCENTRATION = 3888 mg/l)		CLARIFIER B WITH FEED WELL DIAMETER OF 3 INCHES (FEED CONCENTRATION = 3888 mg/l)	
EFFLUENT SUSPENDED SOLIDS (mg/l)	UNDERFLOW CONCENTRATION (mg/l)	EFFLUENT SUSPENDED SOLIDS (mg/l)	UNDERFLOW CONCENTRATION (mg/l)
11.00	6250	10.35	6200
8.09	6285	8.20	6480
9.00	6490	8.30	6210
8.20	6073	8.06	6190
8.03	7738	7.60	7525
8.10	7050	7.30	7720
6.12		6.40	
7.09		6.07	
7.01		7.20	
$\bar{x}$ = 8.07	$\bar{x}$ = 6648	$\bar{x}$ = 7.72	$\bar{x}$ = 6721
s = 1.38	s = 632	s = 1.25	s = 709
confidence interval (α = 0.05) = $6.18 < \mu < 9.13$	confidence interval (α = 0.05) = $5984 < \mu < 7311$	confidence interval (α = 0.05) = $6.95 < \mu < 8.89$	confidence interval (α = 0.05) = $5977 < \mu < 7465$

TABLE 21

STEADY-STATE REPLICATE ANALYSES
(4/06/85)

CLARIFIER A WITH FEED WELL DIAMETER OF 3 INCHES (FEED CONCENTRATION = 3880 mg/l)		CLARIFIER B WITH FEED WELL DIAMETER OF 5.5 INCHES (FEED CONCENTRATION = 3880 mg/l)	
EFFLUENT SUSPENDED SOLIDS (mg/l)	UNDERFLOW CONCENTRATION (mg/l)	EFFLUENT SUSPENDED SOLIDS (mg/l)	UNDERFLOW CONCENTRATION (mg/l)
7.20	6250	10.50	5960
7.60	7105	10.25	6200
7.26	7110	8.59	6345
10.80	7123	9.20	6970
9.25	7250	9.50	6964
6.80	7280	7.02	7008
7.00		8.90	
8.40		8.54	
6.50		7.80	
6.19		8.30	
$\overline{x}$ = 7.70	$\overline{x}$ = 7020	$\overline{x}$ = 8.86	$\overline{x}$ = 6575
s = 1.41	s = 384.53	s = 1.06	s = 461.86
confidence interval ($\alpha = 0.05$) = $6.79 < \mu < 8.61$	confidence interval ($\alpha = 0.05$) = $6616 < \mu < 7423$	confidence interval ($\alpha = 0.05$) = $7.95 < \mu < 9.77$	confidence interval ($\alpha = 0.05$) = $6090 < \mu < 7059$

TABLE 22

STEADY-STATE REPLICATE ANALYSES
(4/12/85)

CLARIFIER A WITH FEED WELL DIAMETER OF 5.5 INCHES (FEED CONCENTRATION = 3880 mg/l)		CLARIFIER B WITH FEED WELL DIAMETER OF 3 INCHES (FEED CONCENTRATION = 3880 mg/l)	
EFFLUENT SUSPENDED SOLIDS (mg/l)	UNDERFLOW CONCENTRATION (mg/l)	EFFLUENT SUSPENDED SOLIDS (mg/l)	UNDERFLOW CONCENTRATION (mg/l)
10.00	6935	7.10	6382
9.60	6830	6.50	6295
9.60	6470	7.70	6395
8.80	6670	6.15	6409
8.20	7050	5.65	
9.20	7720		
9.80			
8.00			
7.50			
6.00			
$\overline{x}$ = 8.67	$\overline{x}$ = 6946	$\overline{x}$ = 6.62	$\overline{x}$ = 6370
s = 1.26	s = 430.40	s = 0.80	s = 51.36
confidence interval (α = 0.05) = $7.86 < \mu < 9.48$	confidence interval (α = 0.05) = $6494 < \mu < 7397$	confidence interval (α = 0.05) = $5.38 < \mu < 7.86$	confidence interval (α = 0.05) = $6288 < \mu < 6452$

TABLE 23

STEADY-STATE REPLICATE ANALYSES
(4/30/85)

CLARIFIER A WITH FEED WELL DIAMETER OF 2 INCHES (FEED CONCENTRATION = 3770 mg/l)		CLARIFIER B WITH FEED WELL DIAMETER OF 5 INCHES (FEED CONCENTRATION = 3770 mg/l)	
EFFLUENT SUSPENDED SOLIDS (mg/l)	UNDERFLOW CONCENTRATION (mg/l)	EFFLUENT SUSPENDED SOLIDS (mg/l)	UNDERFLOW CONCENTRATION (mg/l)
6.50	5570	8.00	5928
7.50	6060	9.60	6620
6.33	5320	8.50	6100
6.50	5800	9.10	6105
7.60	5520	9.80	6115
7.33	5680	9.01	6120
6.24		8.59	
6.00		9.80	
6.50		8.50	
6.00		8.70	
$\overline{x}$ = 6.65	$\overline{x}$ = 5658	$\overline{x}$ = 8.96	$\overline{x}$ = 6165
s = 0.60	s = 254.28	s = 0.61	s = 234.75
confidence interval (α = 0.05) = $6.27 < \mu < 7.03$	confidence interval (α = 0.05) = $5391 < \mu < 5925$	confidence interval (α = 0.05) = $8.56 < \mu < 9.36$	confidence interval (α = 0.05) = $5918 < \mu < 6411$

TABLE 24

STEADY-STATE REPLICATE ANALYSES
(6/07/85)

CLARIFIER A WITH FEED WELL DIAMETER OF 3 INCHES (FEED CONCENTRATION = 2795 mg/l)		CLARIFIER B WITH FEED WELL DIAMETER OF 5.5 INCHES (FEED CONCENTRATION = 2795 mg/l)	
EFFLUENT SUSPENDED SOLIDS (mg/l)	UNDERFLOW CONCENTRATION (mg/l)	EFFLUENT SUSPENDED SOLIDS (mg/l)	UNDERFLOW CONCENTRATION (mg/l)
6.00	5310	11.00	5172
7.10	5211	9.80	5197
4.02	5820	10.90	5390
6.00	5792	9.75	5319
5.48	5281	9.80	5295
4.28		10.41	
5.50		9.80	
7.00		9.72	
5.33		8.52	
5.02		8.37	
$\bar{x}$ = 5.57	$\bar{x}$ = 5603	$\bar{x}$ = 9.81	$\bar{x}$ = 5275
s = 1.01	s = 316.07	s = 0.86	s = 89.79
confidence interval (α = 0.05) = $4.73 < \mu < 6.41$	confidence interval (α = 0.05) = $5210 < \mu < 5995$	confidence interval (α = 0.05) = $9.17 < \mu < 10.45$	confidence interval (α = 0.05) = $5163 < \mu < 5389$

REFERENCES

Baker, Kenneth D., and Reed, Gregory D. "Evaluation of Mechanical Flocculation of Activated Sludge for Improvement of Secondary Clarification." Presented at the Water Pollution Control Federation 57th Annual Conference, New Orleans, LA, September 30-October 4, 1984.

Camp, T.R. "Sedimentation and the Design of Settling Tanks." Transactions of the American Society of Civil Engineers 2285 (May 1946): 895.

Dick, Richard I. "Role of Activated Sludge Final Settling Tanks." Journal American Socity of Civil Engineers, Sanitary Engineering Division 96 (April 1970): 424.

Dietz, John D. "Clarification Mechanisms for a Flocculent Slurry." Ph.D. Dissertation, Clemson University, Clemson, SC, 1982.

Dietz, John D., and Keinath, Thomas M. "Experimental Evaluation of the Significance of Overflow Rate and the Detention Period." Journal Water Pollution Control Federation 56 (April 1984): 344.

EIMCO Process Equipment Company. "Feed Well Dimension." 1984.

Fischer, A.J., and Hillman, J.N. "Plant Operation." Sewage Works Journal 12 (March 1940): 280.

Fitch, E.B. "Sedimentation Process Fundamentals." In Biological Treatment of Sewage and Industrial Wastes, Volume II. Edited by B.J. McCabe and W. Eckenfelder. New York: Waverly Press, Inc., 1958.

Fitch, E.B., and Lutz, W.A. "Feed Wells for Density Stabilization." Journal Water Pollution Control Federation 32 (February 1960): 147.

Haley, Steve. Personal Communication. University of Central Florida, Orlando, Florida, 1985.

Joint Committee of the American Society of Civil Engineers (ASCE) and the Water Pollution Control Federation (WPCF). "Sewage Treatment Plant Design." In Manual of Practice, 1959.

Joint Committee of the American Society of Civil Engineers (ASCE) and the Water Pollution Control Federation (WPCF). "Wastewater Treatment Plant Design." In Manual of Practice, 1977.

Knop, Erich. "Design Studies for the Emscher Mouth Treatment Plant." Journal Water Pollution Control Federation 38 (July 1966): 1194.

Loehr, Reynolds C., and de Navarra, Carlos T., Jr. "Grease Removal at a Municipal Treatment Facility." Journal Water Pollution Control Federation 41 (May 1969): R142.

Margio, Joseph. "The Effect of Recycle Control on Activated Sludge Clarification Efficiency." Master's Thesis, University of Central Florida, Orlando, FL, 1985.

McClane, James, and Dietrich, Frank H. "Model Building." In Statistics. New York: McGraw-Hill Book Company, 1985.

Neter, J., and Wasserman, W. Applied Linear Statistical Models: Regression, Analysis of Variance and Experimental Designs. Homewood, IL: Richard D. Irwin, Inc., 1974.

Norris, Pan D.; Parker, Denny S.; Daniels, Marvin L.; and Owens, Eben L. "High Quality Trickling Filter Effluent without Tertiary Treatment." Journal Water Pollution Control Federation 54 (July 1982): 1087.

Novak, John T. "Activated Sludge Processes and Effluent Standards." Journal Water Pollution Control Federation 55 (April 1983): 332.

Parker, Denny S. "Assessment of Secondary Clarification Design Concepts." Journal Water Pollution Control Federation 55 (April 1983): 349.

Parker, Denny S. "Physical Conditioning of Activated Sludge Floc." Journal Water Pollution Control Federation 43 (September 1971): 1817.

Pipes, Wesley. "Bulking, Deflocculation and Pin Point Floc." Journal Water Pollution Control Federation 51 (January 1979): 62.

Reynolds, Tom D. "Sedimentation." In Unit Operations and Processes in Environmental Engineering. Monterey, CA: Brooks/Cole Engineering Division, 1977.

Sawyer, Clair N. "Final Clarifier and Clarifier Mechanisms." In Biological Treatment of Sewage and Industrial Wastes, Volume I. Edited by B.J. McCabe and W. Eckenfelder. New York: Waverly Press, Inc., 1956.